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# TECHNOLOGY ASSESSMENT OF RING LASER GYROSCOPES



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JULY 1979



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This assessment reviews the laser gyroscope's history from its earliest conceptual formulation and discusses the experiments which led to the first successful application of the instrument in 1963. The basic theory of operation is discussed and a bibliography of related scientific documents currently in the GACIAC file is included as a source of more information. The fundamental problems which have been encountered in the development of the laser gyroscope are discussed and the methods

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DILAG (Differential Laser Gyro)
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Acousto-Optic Frequency Shifters
Dithering
Optical Biasing
Scale Factor
Strapdown Inertial Systems
Control Systems
Inertial Guidance
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Bibliography

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currently used to overcome them are reviewed. In its purest form and without any corrections, the laser gyroscope would be characteristically unsuitable for tactical weapons use; considering the state of the art in its basic components; but, with suitable mechanical or optical biasing accessories it becomes quite useful for short range tactical requirements and platform stabilization.

The laser gyroscope presents a radical approach to the design of position measuring instruments. Unlike its predecessor, the gimbaled gyroscope with all of its mechanically moving parts, the laser gyroscope is a solid state device with no moving parts, and as such is especially suited for strapdown inertial guidance system application. Besides its design simplicity, it possesses many other attractive features, such as ruggedness, instant-on capability, insensitivity to temperature and environmental variants, an extremely broad measurement range, consistency from turn on to turn on, a longer shelf and operational life, longer recalibration intervals, and lastly, a lower lifetime cost of ownership. Because of these desirable features, the laser gyroscope has generated a great deal of excitement leading to a number of development programs aimed at applications throughout the guidance and control community for both commercial and military uses.

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# TECHNOLOGY ASSESSMENT OF RING LASER GYROSCOPES

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# PREFACE

This technical assessment was prepared by the Tactical Weapon Guidance and Control Information Analysis Center under Contract DSA 900-77-C-3840, for the U.S. Army Missile Command (MICOM). It is intended to cover the basic concepts of ring laser gyroscopes, the various aspects of which have been touched upon by many authors, and to provide a source of reference material for those interested in this direction measuring system.

Much of the material used in this technical assessment was based on the quoted references and does not represent original work.

This assessment reviews the laser gyroscope's history from its earliest conceptual formulation and to the present applications of the instrument. Inherently, the laser gyroscope has many desirable features as compared to its mechanical counterpart, the gimballed gyro. For this reason, the laser gyroscope has generated a great deal of excitement leading to a number of development programs aimed at applications throughout the guidance and control community for both commercial and military uses.

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## 1. INTRODUCTION

The ring laser gyroscope is a relatively young concept in gyroscopic devices which has provoked a great deal of interest and work and which may be destined to revolutionize the future methods of position measurement. A solid state device unlike its predecessor, the gimbaled gyroscope, its expanded use may be likened to the widespread use of the quartz watches of today over the mechanical watches of yesterday.

This document initially will review some of the laser gyroscope's history and basic formulation. The major portion will broadly cover the technical aspects of the device to a reasonable depth; however, many references are cited by which the reader can pursue the subject onto a very high technical level. A chronological bibliography is also presented of documents currently available in the GACIAC library which cover the subject from its beginning and includes its many ramifications.

In addition to the discussion of the fundamentals of ring laser gyroscopes, the device's shortcomings and error sources are also discussed along with the methods currently being used or experimented with to overcome the errors. A short discussion of possible applications completes this review.

## 2. GYROSCOPES - HISTORICAL DEVELOPMENT

The device we know today as the gyroscope is really the evolution of an ancient toy, the spinning top, which predates the Christian era. However, the fact that the spinning top could be useful in some way as a scientific instrument was not recognized until the year 1752 (Reference 1) with the first publication on a gyroscopic device. About ten years before, an ingenious mechanic, Serson, recognizing the property of a spinning top to affect a vertical position, produced a crude gyroscope, intending to create an artificial horizon. A gyro sextant was developed and built using the Serson device and tested successfully in 1743; however, little or no additional work was done on the stabilized sextant for over 100 years. In 1852, the term "gyroscope" was first used by the French scientist Leon Foucault in a memoir read before the Academy of Sciences in Paris. He used a gyro in an attempt to demonstrate and measure the rotation of the earth. This experiment, called the "first gyro experiment of Foucault", was based on the fact that a gyro, properly suspended, retains the direction of its spin axis in space when its supports are rotated. The experiment was really unsuccessful in determining the earth's rotation rate, but it did lead to further experiments and the eventual development of the gyro compass and the gyro stabilizer. These experiments were conducted by many scientists in searching for applications of the gyro, including Sperry, who was instrumental in several developments such as an artificial horizon, a gyro compass, huge ship stabilizers, and the gyro stabilization of aircraft using an autopilot.

Today, gyroscopes have evolved into extremely sensitive and high precision instruments for the measurement of direction. These devices are used for artificial horizons, gyro compasses, directional gyros, rate gyros, autopilots and accurate inertial navigation systems for military and civilian use.

Gyroscopes developed thus far were mechanical in nature, using a spinning wheel, or mass, called a rotor mounted in a

frame called a Cardan-suspension or gimbals. This is the gyroscope configuration familiar to most people. These conventional gyroscopes using the spinning mass as the sensing element (subject to Newton's first law) have many sources of error, leading to inaccuracies which are very costly to minimize.

Bearing friction, spin motor wear, unbalance of the rotor, mechanical structures subject to environmental temperatures, and "spin up" time are some of the problems that must be overcome in the design and construction of mechanical gyros. This results in the need for precision machining requirements, complicated assemblies, and rigid manufacturing processes, which make the device very costly. In addition, auxilliary hardware is required for voltage control and temperature control, necessary to obtain high accuracy. This adds to the cost. Periodic maintenance and recalibration are also necessary, which though not an initial cost, must be considered in the overall cost and down time of the unit.

Now, after 200 years of development, the mechanical gyroscope is being replaced by a new generation of direction measuring devices, the laser gyroscope, which shows promise of being less costly and more dependable than its predecessor.

# 3. LASER GYROSCOPE

## 3.1 Introduction

The laser gyroscope is a solid state, integrating rate gyroscope that measures inertial rotation rates with high precision. In its simplest form, the laser gyroscope has no mechanical or moving parts, is not subject to temperature extremes, is ready for use in a fraction of a second and does not require periodic calibration and maintenance. It is a compact device adaptable for use in short range tactical missiles, aircraft inertial navigation systems, stabilization devices for shipboard gun control systems, attitude control and as a north finding compass. The gyroscope will perform in very high g environments and having no mechnical parts, requires little or no maintenance or calibration.

The laser gyroscope is not, however, without its faults, one of which is the inability to match the high accuracy and low drift rates of conventional gyroscopes.

## 3.2 Development

A significant step in the development of the laser gyroscope occurred in 1913 and is attributed to Sagnac (Reference 2), who demonstrated the feasibility of an optical system capable of measuring the state of rotation of a frame of reference, using an optical interferometer, in which the interferometer was at rest.

The principal of Sagnac's interferometer is shown in Figure 1. A light beam coming from the source A is split at the beamsplitter, B, into a beam circulating the loop in a clockwise direction and a beam circulating the loop in a counterclockwise direction, with both beams reunited at B so that interference fringes are observed at D. When the entire interferometer is rotated at an angular rate of $\omega$ radians per second, the detected fringe shift, $\Delta Z$, is given by the relation,

$$\Delta Z = \frac{4A\omega}{\lambda c} \tag{1}$$

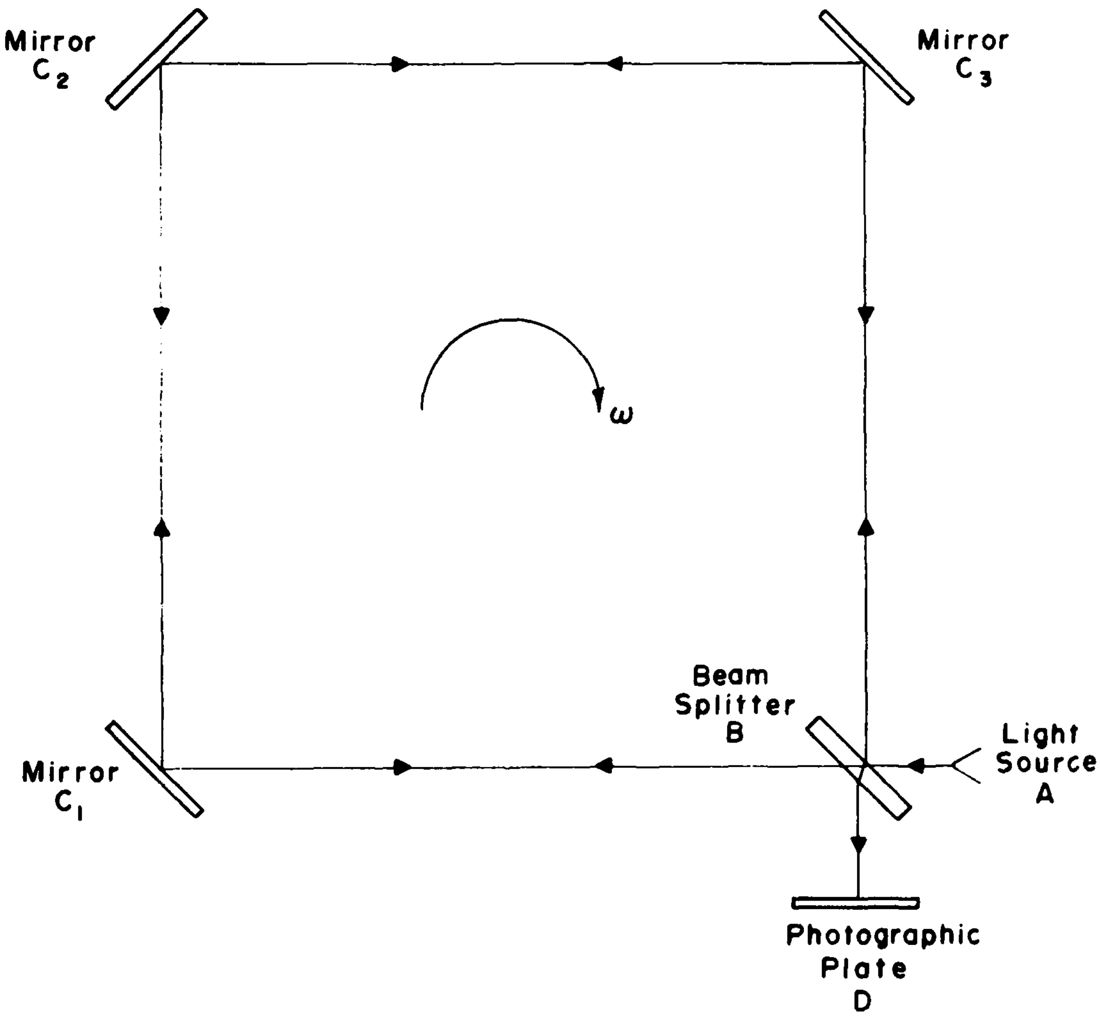



Fig. 1 SAGNAC INTERFEROMETER

where

A = the area enclosed by the light path,

$\lambda$ = the vacuum wavelength,

c = the velocity of light.

In the interferometer, the frequency is determined by the source, and as such, the contra-rotating beams are of the same frequency. As the system rotates, however, the time it takes for each of the contra-rotating beams to traverse its respective path is different, so at the point of recombination the output will have a phase difference that is dependent on the rotation rate of the system. This effect can be explained as follows. Consider the ideal circular interferometer of radius R (Figure 2). The light directed at the beamsplitter at A is represented by a quantum of electromagnetic energy, or photons. One photon is reflected from the surface of the beamsplitter and travels in a clockwise direction around the optical circuit, while another photon passes through the beamsplitter and travels in a counterclockwise direction around the optical circuit. The photons travel at the speed of light, c. When the interferometer is stationary, the transit time, t, for each of the photons to traverse the physical path length of the interferometer is given by $2\pi R/c$, where $2\pi R$ is the path length.

Assume now that the interferometer is rotated in a clockwise direction at a constant angular velocity, $\omega$ (radians/unit time). While the device is rotating, the closed path transit time from the beamsplitter around and back to the beamsplitter becomes quite different for the contra-rotating photons. This is because during the transit time of the photons, the beamsplitter is angularly displaced from position A to a new position, A'. Now, with respect to inertial space, the photon traveling with the clockwise direction of the rotating interferometer must traverse a distance greater than the distance $2\pi R$, while the photon traveling against the interferometer rotation will traverse a distance shorter than $2\pi R$ in order for each beam, respectively,

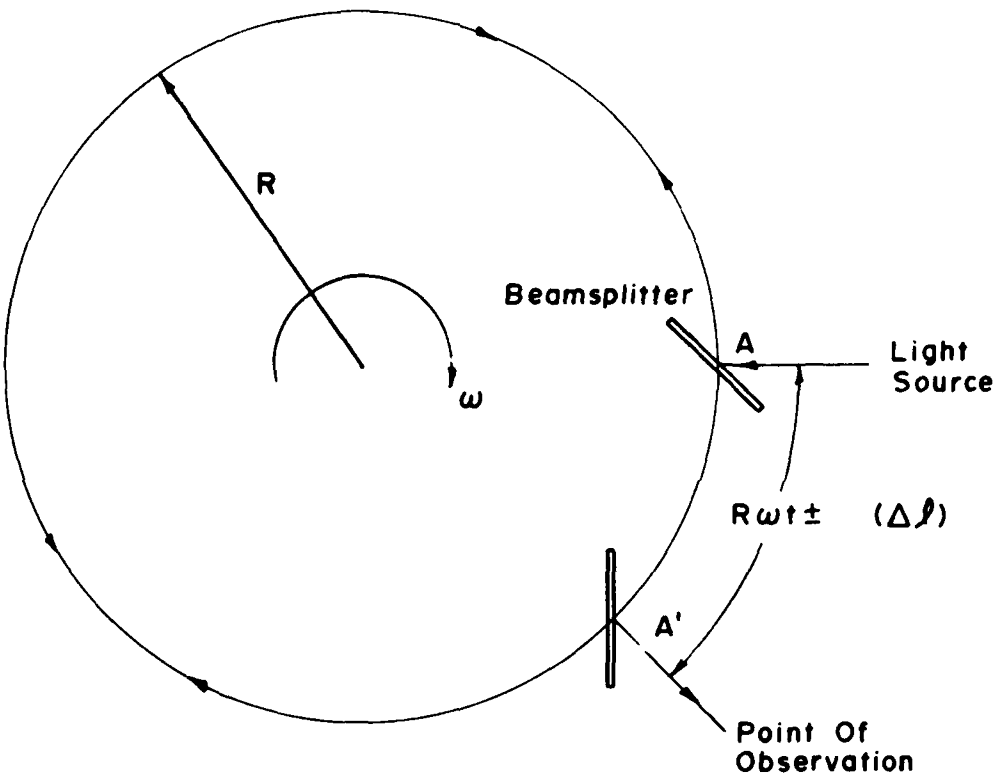



Fig. 2 CIRCULAR ROTATING SAGNAC INTERFEROMETER

to reach the new position of the beamsplitter at A'. The speed of light, c, being a constant, the travel time taken by each of the photons will also be different.

The inertial distance between A and A' is given by $R\omega t_{\pm}$. The distance traversed by each of the contra-rotating photons would be

$$ct_{\pm} = 2\pi R \pm R\omega t_{\pm}, \tag{2}$$

where $t_+$ is the transit time of the photon rotating in the direction of the rotating interferometer and $t_-$ is the transit time of the other. In terms of time, Eq. 2 becomes

$$t_{\pm} = \frac{2\pi R}{c \mp R\omega} \tag{3}$$

The differential time of travel, $\Delta t$, between the contra-rotating photons is given by

$$\Delta t = t_{\pm} - t_{-} \tag{4}$$

or,

$$\Delta t = \frac{2\pi R}{c-R\omega} - \frac{2\pi R}{c+R\omega},$$

$$\Delta t = \frac{2\pi R^2\omega}{c^2-R^2\omega^2} + \frac{2\pi R^2\omega}{c^2-R^2\omega^2},$$

since $c^2 >> R^2\omega^2$,

$$\Delta t = \frac{4\pi R^2\omega}{c^2} \tag{5}$$

The area, A, of a circle is given by $\pi R^2$; therefore

$$\Delta t = \frac{4A\omega}{c^2} \tag{6}$$

which is the fundamental equation for the rotating interferometer.

### 3.3 Other Interferometer Shapes

A square interferometer, similar to the Sagnac experiment (Figure 3a), and an equilateral triangle interferometer (Figure 3b), which is, in fact, the predominant laser gyro configuration, are now examined.

Consider the square of Figure 3a, of side length 2R and perimeter 8R. Assume the square encloses a circle of radius R. The distance traversed by a photon in a stationary system is 8R. Again, assume the interferometer is rotated in a clockwise direction at a constant angular velocity, $\omega$, resulting in the repositioning of the device a very small distance, $\Delta\ell$.

Assuming $\Delta\ell$ to be much less than 8R, $\Delta\ell$ will be approximated as the arc length of the circle of radius R moving at an angular velocity $\omega$ over the time $t_\pm$, and again is given by $R\omega t_\pm$. This distance traversed by the contra-rotating photons in a rotating system is

$$ct_\pm = 8R \pm R\omega t_\pm \; . \tag{7}$$

In terms of time,

$$t_\pm = \frac{8R}{c \mp R\omega} \; .$$

In terms of differential time,

$$\Delta t = \frac{8R^2\omega}{c^2} + \frac{8R^2\omega}{c^2} \; , \tag{8}$$

$$\Delta t = \frac{16R\omega}{c^2} \; . \tag{8}$$

The area, A, of the square is given by $4R^2$; therefore,

$$\Delta t = \frac{4A\omega}{c^2} \; ,$$

the fundamental equation for the rotating interferometer.

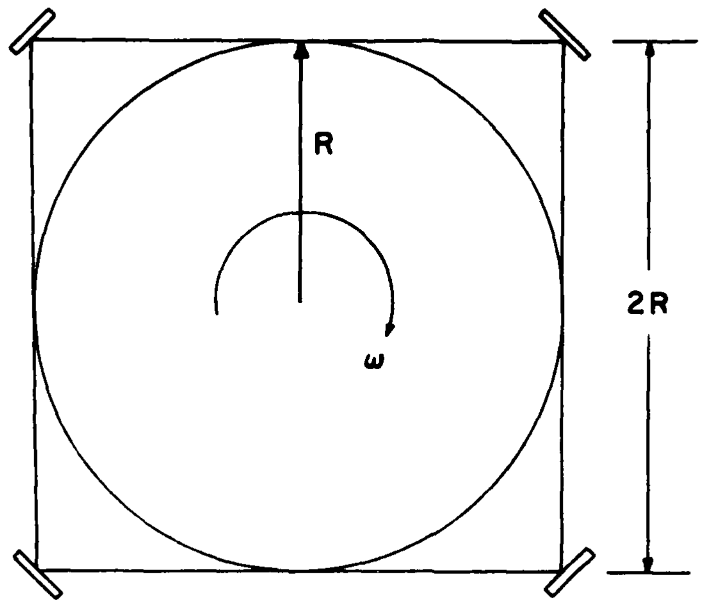



Fig. 3a SQUARE MODEL INTERFEROMETER

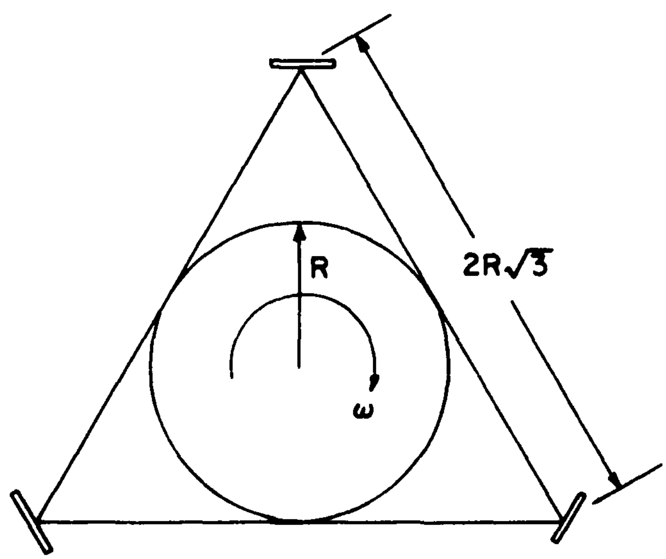



Fig. 3b EQUILATERAL TRIANGLE MODEL INTERFEROMETER

Considering the equilateral triangle of Figure 3b of side length $2R\sqrt{3}$ and perimeter of $6R\sqrt{3}$, the distance traversed by a photon in a rotating system is

$$ct_{\pm} = 6R\sqrt{3} \pm R\omega t_{\pm} \tag{9}$$

Again, assuming $\Delta\ell << 6R\sqrt{3}$ and considered as the arc length of a circle of radius R enclosed by the triangle. In terms of time,

$$t_{\pm} = \frac{6R\sqrt{3}}{c \mp R\omega} .$$

In terms of differential time,

$$\Delta t = \frac{6R^2\sqrt{3}\omega}{c^2} + \frac{6R^2\sqrt{3}\omega}{c^2}$$

$$\Delta t = \frac{12R^2\sqrt{3}\omega}{c^2} . \tag{10}$$

The area, A, of the equilateral triangle is given by $3R^2\sqrt{3}$; therefore,

$$\Delta t = \frac{4A\omega}{c^2} ,$$

again, the fundamental equation for the rotating interferometer.

The optical path difference, $\Delta\ell$, is given by $c\Delta t$; therefore, from Eq. 4

$$\Delta\ell = \frac{4A\omega}{c} . \tag{11}$$

This equation, then, is generalized for any enclosed optical configuration and shows that the path difference is proportional to the enclosed area and the rotational velocity.

Although the axis of rotation is assumed to be at the center of the system, it can be shown that the optical path difference given by Eq. 11 is independent of the location of the axis.

The fringe shift observed using the Sagnac interferometer and as described by Eq. 1 is proportional to the area circumvented

by the device. Since the measure of rotation rate is the phase difference resulting from the difference in path length, and since the path length difference is much less than a wavelength, a device having a large area is required in order to observe a measurable fringe when measuring low rotation rates. In 1925, Michelson and Gale measured the rotation rate of the earth normal to the device, which was located near Chicago, by using an optical path length of about one nautical mile (Reference 3). The configuration was a rectangle with sides 2010 by 1113 feet with an enclosed area of about $2.08 \times 10^5$ square meters. The large size was necessary to produce a measurable path difference, $\Delta\ell$, at the rotation rate of the earth. In this experiment, the measured path difference amounted to about 1300 Å or about ¼ fringe.

3.4 Ring Laser Interferometer

The Sagnac interferometer, because of size requirements and lack of sensitivity, would not be useful as a practical gyroscope. Although Michelson and Gale used broadbanded monochromatic light as the external source, using a laser as the external light source would not improve the operation because the optical path difference would be much less than a wavelength. The solution is an active optical oscillator set into a closed, or ring, optical cavity. For this ring interferometer to be useful for measuring small length changes a device is required whose frequency is dependent on the length of the optical path traversed. In this way the signals of two independent oscillators, each having a frequency dependent on the optical cavity length can be transformed into a measurable difference, or beat frequency, that would be a measure of length difference. This is accomplished by placing two laser oscillators into the optical path, thereby creating an active interferometer, and making the laser frequency dependent on the optical path length. Figure 4 shows a laser gyro optical diagram. One leg of the triangle is notched out to facilitate a gas discharge tube containing a mixture of helium and neon. At certain wavelengths, light will experience gain

as it passes through the gas discharge. This gain is fixed so that losses due to the reflecting mirrors, diffraction, and other causes are equalized.

When the gas discharge tubes are energized, two contra-rotating light beams traverse the optical path, each an independent frequency. The oscillation frequency for the reinforcement of the light waves, that is, the lowest order transverse mode, requires that the optical path length, $\ell$, be exactly equal to an integer number of wavelengths. The system would not lase otherwise. The ability to generate and sustain stable contra-rotating oscillations in a ring laser was first demonstrated in 1963 by Macek and Davis of Sperry Rand (Reference 4) in their experiment to sense rotation rate with a ring laser. The device built then for the laboratory experiment was the very first laser gyroscope.

The basic requirement is that the laser wavelength must be an integer, N, fraction of the optical path length, or,

$$N\lambda = L \quad . \tag{12}$$

The value of N is usually in the order of one million. In terms of frequency,

$$f = \frac{Nc}{L} \tag{13}$$

Now, small changes in path length result in small changes in frequency,

$$\frac{\Delta f}{f} = \frac{\Delta L}{L} \tag{14}$$

The resulting beat frequency, $\Delta f$, can be related to the rotation rate, $\omega$, from Eq. 11, given as

$$\Delta\ell = \frac{4A\omega}{c} \tag{15}$$

Substituting Eq. 14 into Eq. 11 yields

$$\Delta f = \frac{4A\omega}{\ell\lambda} \tag{16}$$

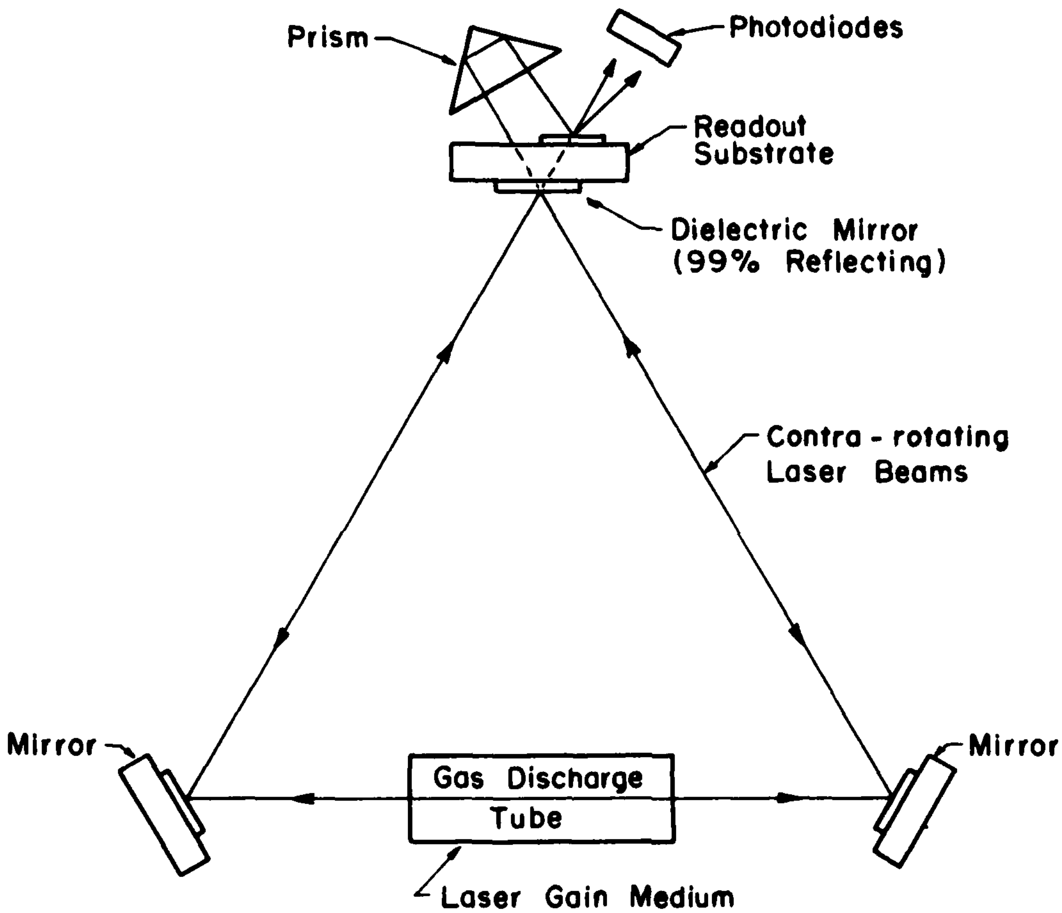



Fig. 4 RING LASER GYROSCOPE BASIC ELEMENTS

Using this principal, beat frequencies on the order of a few Hertz would be produced for rotation rates of a few degrees per hour, using perimeter lengths of less than 12 inches. Since these beat frequencies amount to only about $10^{-14}$ of the optical frequency, the sensitivity of such an active optical oscillator, or ring laser gyro, is much greater than the interferometer technique, and permits low rotation rates to be measured using devices having a fairly small size.

### 3.5 Laser Gyroscope Output

Since the difference in the optical frequencies of the contra-rotating beams is proportional to the angular turning rate, output information is obtained by monitoring the difference frequency. Of course, if the laser gyro were not rotating, the contra-rotating beams would be equal in frequency, resulting in zero difference frequency. If the laser gyro were rotating uniformly, the beat frequency would be a constant, proportional to the turning rate.

A direct measurement of the beat *frequency* is accomplished by combining the contra-rotating beams using optics so that they are parallel. Figure 4 shows an optical method for combining the beams to obtain a readout. Less than 0.1% of the incident light of both beams is transmitted through the optical coating of the output mirror. The wavefronts of the two beams will interfere with each other, because of the frequency differential, and will alternately reinforce or cancel forming a fringe pattern. The fringe pattern will move in either direction depending on the direction of rotation of the laser gyro. Each fringe represents one cycle of phase change between the two beams. Two photo diodes are used to sense the direction of movement of the fringe pattern. Dimensions of the detector are much smaller than the spacing between the fringes. As the intensity maximum moves past the detector, a signal is generated whose frequency is proportional to the input turning rate.

Because of the digital output, the laser gyro is inherently an integrating rate gyro. A pulse count determines the rotation

angle of the gyro as a function of time and is independent of variations in the rotation rate. The number of counts as a function of angular displacement is referred to as the gyroscope's scale factor (SF), and can be expressed as counts per radian, counts per arcsecond, or more commonly, arcseconds per count. From the relationship of $\Delta f/\omega$ and SF, and, substituting Eq. 16 yields,

$$SF = \frac{4A}{L\lambda} \quad \text{counts per radian,} \tag{17}$$

where each count is a $2\pi$ phase difference between the two beams. For example, the Honeywell RLG GG 1328, having an equilateral triangle perimeter length of 8.4 inches and a laser wavelength of 0.6328 microns, has a scale factor of about 65,000 counts per radian. The reciprocal scale factor is 3.147 arcseconds per count (Reference 5). A 360° circle is equivalent to 1,296,000 arcseconds; therefore, turning this gyroscope through one complete revolution would result in 411,821 counts. If this gyroscope were in inertial space, rotating it through a complete revolution first in one direction and then the other would result in a zero pulse count.

## 3.6 Laser Gyroscope Errors

### 3.6.1 Lock-In

Lock-in is a phenomenon common to closely coupled electromagnetic oscillators. In electronic oscillators the frequency of a tank circuit can be perturbed by the injection of another signal operating at a frequency very close to that of the free running oscillator. That is, at some critical combination of signal strength and frequency difference, a free running oscillator will lock to the external signal. Similarly, in a ring laser gyroscope, a mutual coupling will exist between the two contra-rotating beams when the rotation rate becomes quite small. The result is the frequency differential goes to zero causing a zero output before the turning rate goes to zero. Backscattering, caused by imperfections in the mirror coatings, allows a small portion of the energy of each of the contra-

rotating beams to be refelected into the path of the other beams, resulting in the locking of contra-rotating beam frequencies. Depending on the lock-in threshold value of the particular device, no rotation rate values can be measured below it. Figure 5a shows the differential output frequency as a function of rotation rate, illustrating the effects of lock-in. As an example of a fairly representative gyroscope, at high turning rates (>10° to 20° per second) the differential frequency is proportional to the input rate, resulting in a linear output. At lower turning rates (<5° per second) the output becomes quite nonlinear, and at the lock-in rate (about 0.01 to 0.1 degrees per second or one-tenth to one revolution per hour) the output goes to zero. Navigation requirements are on the order of 0.01 degrees per hour.

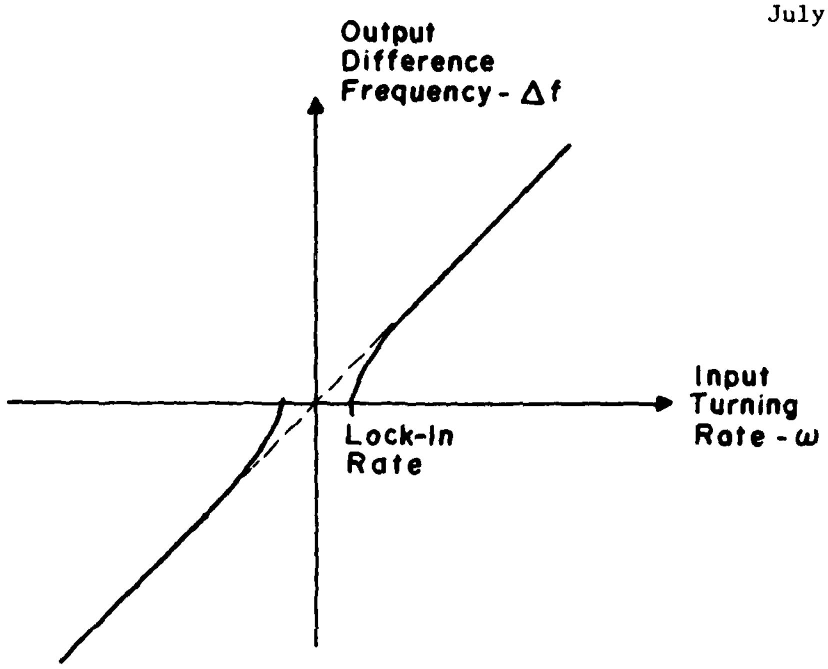
### 3.6.2 Laser Gyro Biasing

Lock-in is a fundamental inadequacy of the laser gyro; however, it has been largely overcome with two methods of laser biasing, mechanical rotation and magnetooptical elements. Laser biasing applies a known turning rate to the gyro, moving the operating point of the gyro away from the lock-in point. Input to the gyro, then, is the sum of the bias rate and the actual input rate. When measuring the actual output rate, the bias must be subtracted from the measured rate.

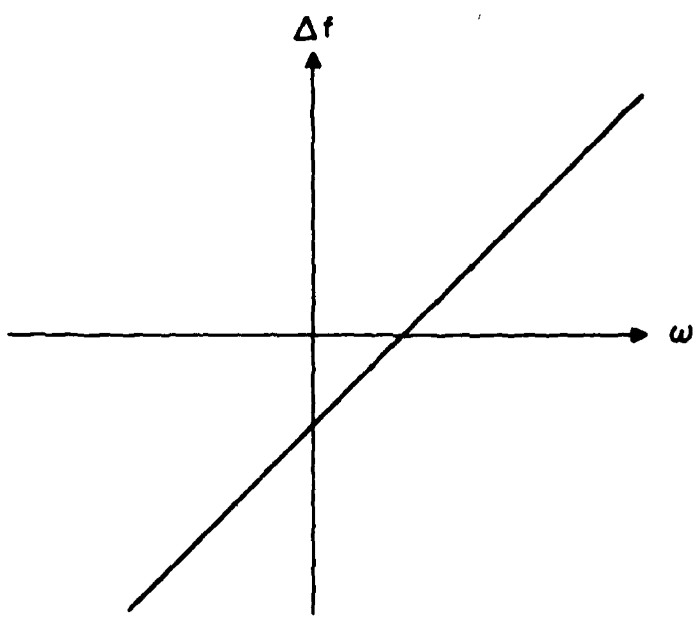
#### 3.6.2.1 Bias Stability

A fixed DC bias, either mechanical or electrooptical, requires very good stability to eliminate any gyro errors caused by bias drift. For example, in order to measure input rates of 0.1 degree per hour using a fixed bias of $10^5$ degrees per hour (about 46 rpm) a bias stability of $10^{-6}$ would be required. This would require a high degree of magnetic and thermal stability.

An alternating bias technique overcomes the bias stability problem. Since the laser gyro is an integrating rate gyro, an oscillating bias technique in which the bias alternates between positive and negative states (sinusoidally or square wave) would result in only the net rotation angle appearing in the output.




a) Lock-In Error




b) Null Shift Error

Fig. 5 LASER GYROSCOPE ERRORS

The laser gyro is biased out of the lock-in range most of the time. This oscillation bias technique reduces the requirements on the absolute stability of the magnitude of the bias. The oscillating bias technique can be employed by using either magnetooptical devices and varying the magnetic field of the bias element, or by mechanically (dithering) oscillating the entire gyro.

#### 3.6.2.2 Mechanical Dithering

Mechanical dithering is a technique by which the entire laser gyro is oscillated about its input axis at a sinusoidal or square wave rate. This laser biasing technique is accomplished by mechanically dithering the laser block at high frequency through a stiff dither flexure suspension built into the gyro assembly. Springs on each side of the laser block suspend it from the center post. Piezoelectric transducers on one of the springs provide the dither drive mechanism to vibrate the block about the input axis. The dither rate amplitude and acceleration are designed so that the dwell time in the lock-in zone (at twice the dither frequency) is short, such that lock-in will never develop (Reference 6). Angular velocities range from 50 to 250 degrees per second and the oscillation frequency varies from 100 Hz to 500 Hz, depending on the manufacturer and the instrument (Reference 5). Subtracting the dithering bias from the output is either done optically, by mounting the optical output detector on the undithered instrument case, or electronically.

#### 3.6.2.3 Magnetooptical Biasing

Magnetooptical biasing elements, when placed in the optical path of the laser light, present a path that appears longer for the light going in one direction than for light going in the opposite direction. The apparent difference in the optical path lengths of the contra-rotating beams causes them to oscillate at different frequencies, resulting in an apparent rotation rate set apart from the lock-in range. There are two such devices used in ring laser gyros, Faraday cells and magnetic mirrors.

#### 3.6.2.4 Magnetic Mirror Biasing

Magnetic mirror biasing is a technique which, unlike the real mechanical rotation applied by dithering, employs an artificial oscillatory bias applied to the gyro to introduce an apparent rotation. A magnetic coating on the mirror, when saturated by an applied magnetic field, causes a differential phase delay between the contra-rotating beams, biasing them away from the lock-in frequency (Reference 7). The resulting bias placed on the gyro is controllable by the applied magnetic field. Bias uncertainties are compensated for by using a square wave alternating biasing technique. Operating in a saturated bias state eliminates error susceptibility to stray magnetic fields (Reference 6).

#### 3.6.2.5 Faraday Cells

The Faraday cell is made of a magnetically active material that has the effect of increasing the optical path length of light passing through it. It is a transmissive device that is placed in one of the legs of the optical cavity. The Faraday cell's index of refraction to circularly polarized light is altered by the applied magnetic field. Because the laser gyros use plane polarized light, quarter wave plates are used to circularly polarize the entering light and plane polarize the exiting light. A change in the optical path lengths of the contra-rotating beams is created, resulting in a difference frequency away from the lock-in range. Bias errors are cancelled by using square wave alternating control fields.

Faraday cells generally require magnetic shielding around the gyro to minimize magnetically induced error effects. Additional limitations of the Faraday cell have been the introduction of thermal and acceleration sensitive bias errors through birefringent and anisotropic effects. The latter error can be decreased by reducing the length of the Faraday cell, but this causes a reduction of bias capability which, in turn, generates scale factor nonlinearities due to the inability to keep the average rate into the gyro outside of the lock-in region (Reference 6).

### 3.6.3 Bias Technique Advantages

Magnetooptical biasing has the advantage of developing an artificial rotation of the laser gyro electrically, without the need of mechanical devices. Another advantage is the ability to generate a square wave bias that has a low frequency and a rapid traversal rate through lock-in, lowering random noise generated from this error source (Reference 6).

Any altering bias technique should be perfectly symmetrical to avoid generating a DC drift term. Mechanical bias avoids this since the motion is physically bounded, negating long term accumulated drift. Also, large bias requires high counting rate circuits and large (MHz) bandwidths. With mechanical bias, it is possible to design the readout system such that the motion of the fringe pattern due to the bias is compensated by the mechanical bias motion. Bias counts are not detected and smaller bandwidth circuitry can be used (Reference 8).

### 3.6.4 Null Shift

When the optical cavity is anisotropic it will exhibit different property values when measured along the optical path in the two opposite directions. Since the laser frequency is a function of the optical path length, any anisotropic effects will result in the two waves oscillating at different frequencies while the device is at rest. This results in a null shift of the output as shown in Figure 5b.

Another source of null shift error is due to the DC current used to excite the laser gyroscope. When a gas discharge is sustained with a DC current the gas flows in the discharge cavity. The gas flows toward the cathode in the center of the discharge and back to the anode close to the cavity walls. The laser energy is concentrated in the center of the cavity. The gas flow toward the cathode produces a shift in the index of refraction depending on the relative directions of the laser energy and the gas flow. The cavity will appear longer in one direction compared to the other and will produce a null shift.

By constructing the laser gyroscope in a balanced configuration, with one cathode and two anodes, such that the current effects are cancelled since the energy traveling around the cavity passes through gas traveling both with and against the laser energy, this effect is reduced. The two anode currents are also balanced to help reduce this effect. Figure 6 shows the construction of a laser gyroscope and Figure 7 shows the gas flow path in a DC laser discharge (Reference 9).

### 3.6.5 Drift

Drift is the laser gyroscope error that remains and is principally due to Faraday cells and magnetic mirrors, when used as biasing elements, and to bulk flows of the excited neon atoms in the laser gas (Reference 5). The latter is due primarily to DC discharge current in the laser gas and thermal gradients along the walls. Normally, the discharge currents in the two arms are balanced; however, instability and noise of this balance will cause drift.

Temperature of the whole device will also effect drift by changing the optical path dimensions or by changing the position of the reflecting mirrors.

## 3.7 Differential Laser Gyroscope (DILAG)

Lock-in at low turning rates is the major fault of two wave laser gyros, but can be overcome by mechanically or electrically dithering the gyro away from the lock-in range. Both techniques, however, have imperfections as already discussed. The application of a large fixed bias fails also, because of noise, drift, and environmental sensitivity of the biasing elements. A four wave ring laser gyro (Figure 8) is an optical bias concept that overcomes the biasing problems of the two-wave gyros by reducing the influence of scattering from the mirrors without resorting to DC biasing. The four wave laser gyro is also referred to as a multi-oscillator, a four mode, or, most often, the differential laser gyro (DILAG).

With the four wave laser gyro concept, a pair of two wave laser gyros operate within the same optical path. One pair of

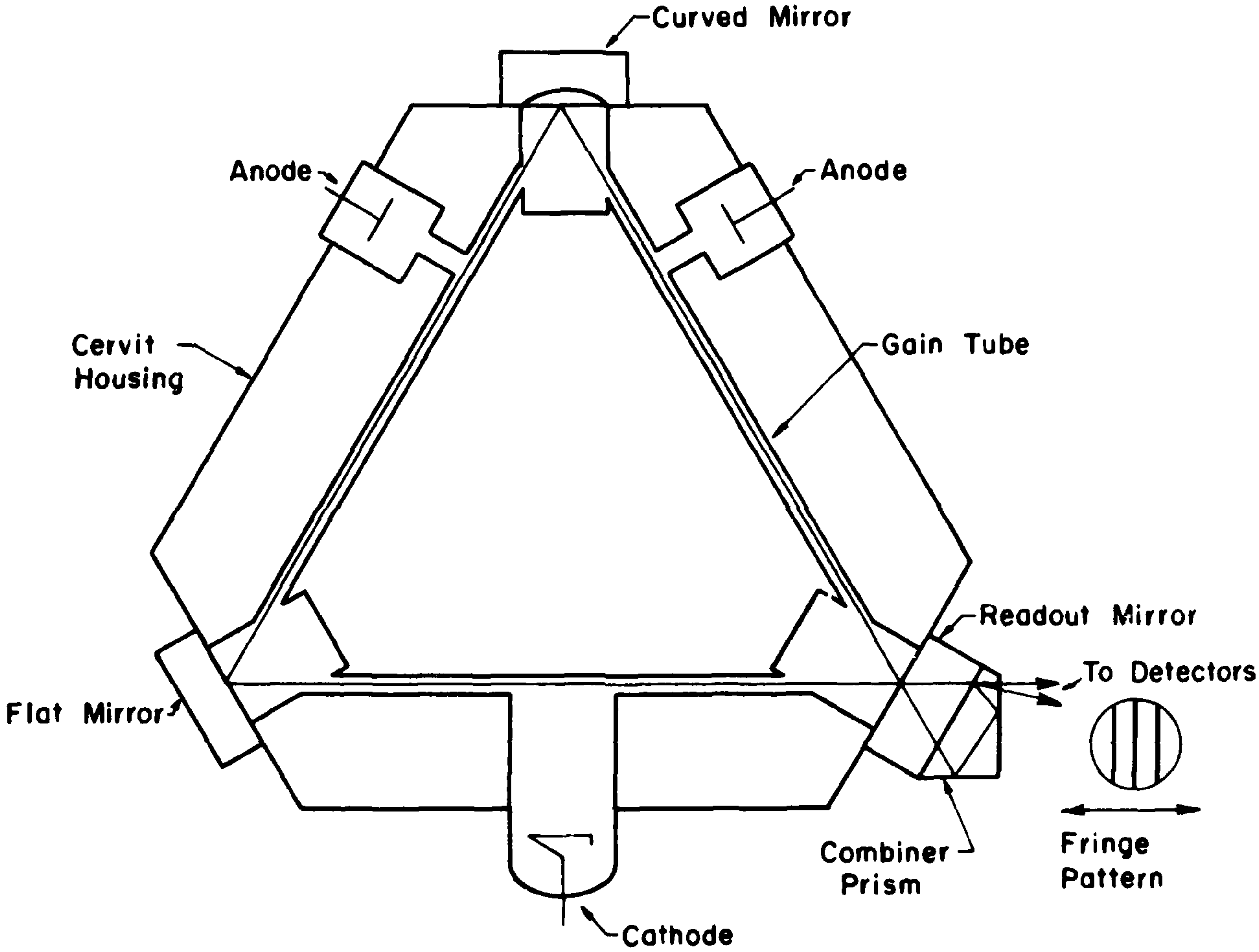



Fig. 6 FUNDAMENTAL LASER GYROSCOPE CONSTRUCTION

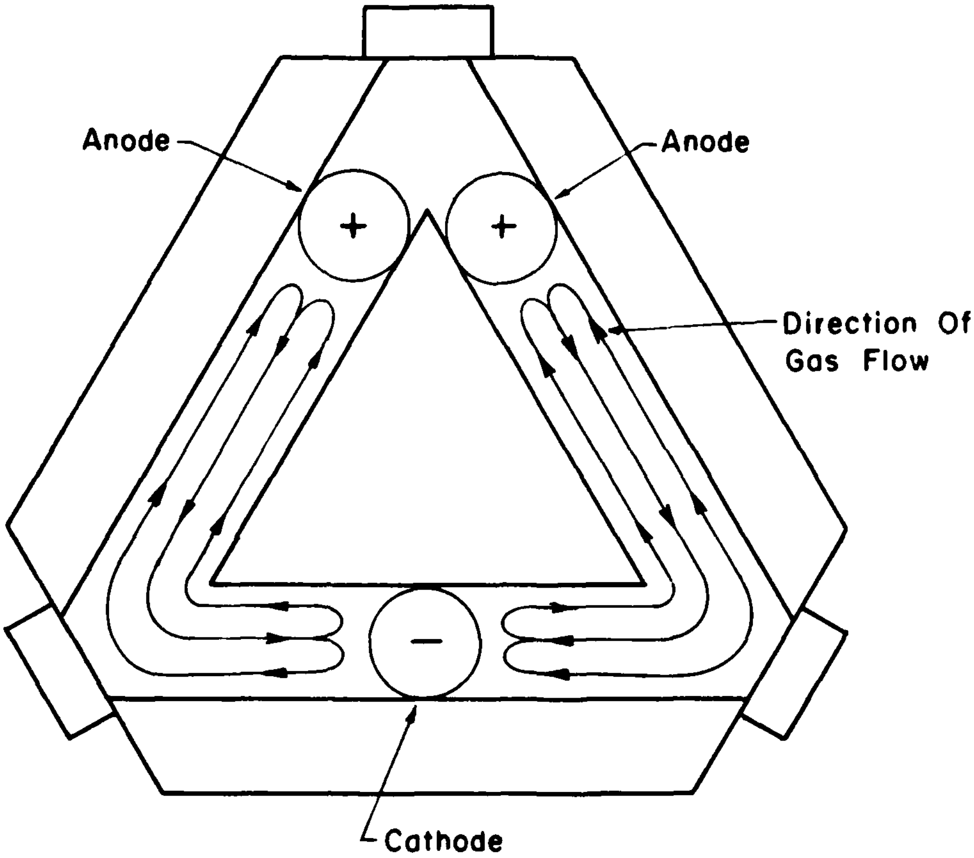



Fig. 7 GAS FLOW IN A DC LASER DISCHARGE

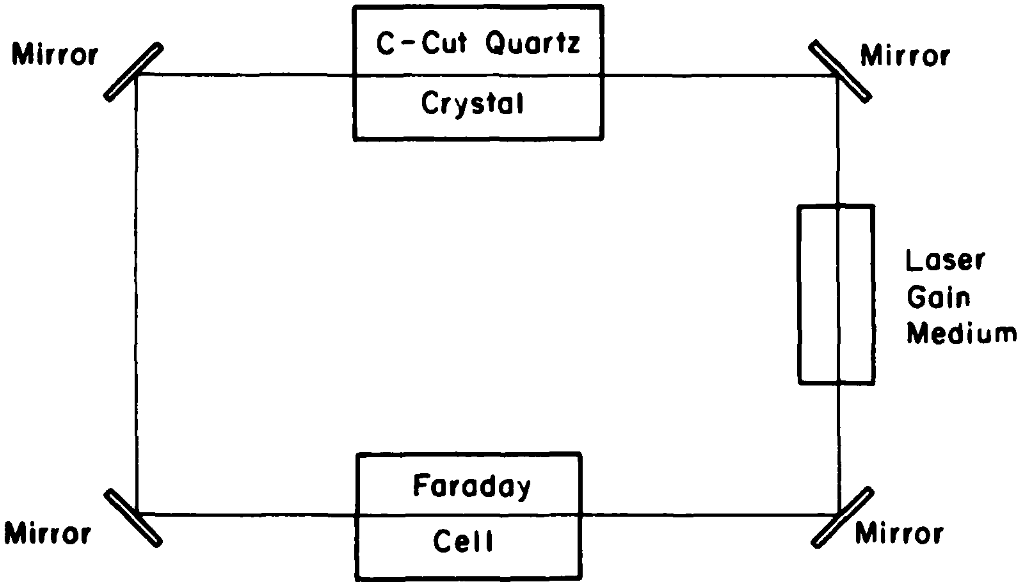



Fig. 8 FOUR WAVE RING LASER GYROSCOPE

traveling contra-rotating waves are right hand circularly polarized and the other pair of contra-rotating waves are left hand circularly polarized. The right circularly polarized and left circularly polarized waves are separated in frequency by many hundreds of MHz by an optical element, historically a C-cut quartz crystal. The Faraday cell biasing element differentiates between the two rotational senses of the circularly polarized waves, independent of direction of wave propagation. The CW left hand and CCW right hand waves have identical path lengths through the element, while the CW right hand the CCW left hand also have identical path lengths through the element. The CCW right hand and CW left hand contra-rotating waves decrease in frequency and the CW right hand and CCW left hand contra-rotating waves both increase in frequency. Applying a rotation to the gyro causes the clockwise and counterclockwise waves to shift in frequency by the same amount as in a two wave laser gyro. The large bias, $\Delta f$, of the Faraday cell results in the CW left hand wave being lower frequency than the CCW left hand wave and the CW right hand wave being higher frequency than the CCW right hand wave. Applying a rotation input, the frequency spacing of one pair of oppositely directed waves will decrease while the other pair will increase. From Eq. 16 and the applied bias

$$f_1 - f_2 = \Delta f - \frac{4A\omega}{\lambda L}$$

$$f_3 - f_4 = \Delta f + \frac{4A\omega}{\lambda L}$$

The resulting beat frequency, $f_b$, is defined as

$$f_b = (f_3 - f_4) - (f_1 - f_2) \ .$$

Substituting from above

$$f_b = \frac{8A\omega}{\lambda L} \ . \qquad (18)$$

Two important features of the four wave laser gyro are apparent from Eq. 18. First, the beat frequency is independent of the bias frequency, $\Delta f$, thereby cancelling any instability in the

biasing element, and second, the scale factor is twice the scale factor of the two wave gyro. Additionally, there is a reduction in coupling because of mirror scattering due to the orthogonality of countra-rotating waves (Reference 5). Scale factor linearity is excellent and is maintained to as low as 1/3 degree per hour (Reference 10).

### 3.8 Passive Ring Resonators

A passive ring resonator has been developed by Ezekiel and Balsamo (Reference 11) based on the use of a passive ring Fabry-Perot interferometer as the rotation sensing element and the use of an external laser to measure any difference between the contra-rotating optical cavity lengths caused by inertial rotation. Since the gain medium is removed from the optical path, associated problems such as lock-in at low rotation rates, bias drift, and scale factor variation are eliminated. One scheme with which experiments have been performed is shown in Figure 9. Two independently controlled laser frequencies are used to measure the CW and CCW resonance frequencies of the passive ring. A single laser and beam splitter form the two laser beams. Crystal devices are used to shift the frequencies of the contra-rotating beams. Measuring the cavity path length difference is done by locking the CW resonance frequency of the cavity to $f_0 + f_1$ by means of an electronic feedback loop using a piezoelectric length transducer. A second feedback loop is used to lock $f_0 + f_2$ to the CCW resonance frequency of the cavity by adjusting $f_2$. The difference between $f_1$ and $f_2$ is directly proportional to inertial rotation.

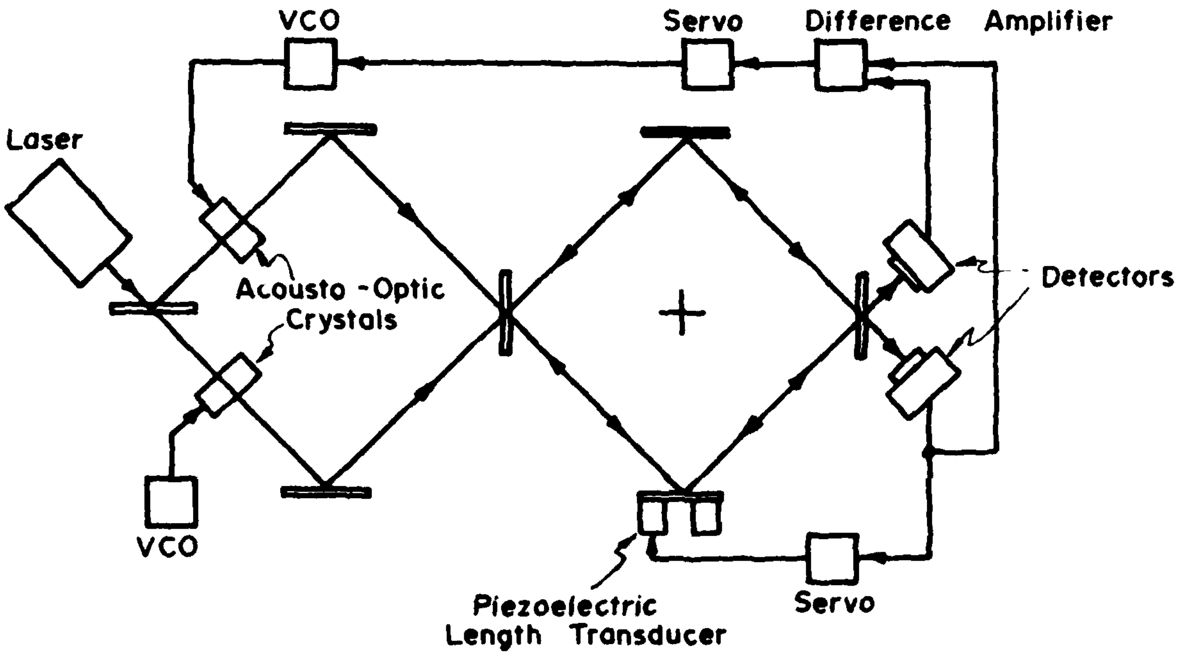



Fig. 9 PASSIVE RING RESONATOR LASER GYROSCOPE

## 4. LASER GYROSCOPE APPLICATIONS

Development of the laser gyroscope has progressed to the point where it is ready for full production. Laser gyroscopes are being considered for the Navy's MK-16 Shipboard Fire Control System and the Advanced Strategic Air Launch Missile (ASALM) (Reference 12). Other systems with application to aircraft navigation both military and commercial, space navigation, and missile guidance are under development. All these systems are based on the strapdown inertial navigator concept. The advent of the low-cost computer has made strapdown navigation the concept of the future. Additionally, present strapdown technology has demonstrated performance in the 1 nmi/hr category similar to that of the classical gimbaled systems, with future production costs estimated to be half of the mechanical systems (Reference 13).

### 4.1 Strapdown Inertial System Characteristics

Inertial navigation systems depend on measurement with respect to a Newtonian reference frame. Conventional gyro systems using gimbals maintain such a reference frame in a stabilized platform, which is isolated from the vehicle being navigated. These systems are mechanically complex and costly, are thermally sensitive, require long turn-on time, and also need frequent calibration. A strapdown navigation system is a variation of this system, but one in which the sensor is physically mounted on the vehicle, turning as the vehicle turns. The transformation from the sensor reference frame to the inertial reference frame is computed using an onboard computer rather than mechanically. This requires an inherently complex computer to analytically perform the functions provided implicitly by the mechanical gimbal assembly. In recent years, low-cost, high-speed digital computers made such computations practical and the strapdown systems a realistic alternate to mechanical systems. The advantage of the strapdown system is the decrease in mechanical complexity because of the elimination of the gimbal assembly.

The laser gyro is a device perfectly suitable for strapdown sensor systems and really has been developed for this application. It meets all the requirements for low-cost digital strapdown missile guidance and control, especially for tactical missile midcourse guidance. Weapon delivery systems require attitude, attitude rate, and linear motion in addition to vehicle velocity and position in a more severe vehicle mounted environment for strapdown systems. A wide dynamic range and high rate performance (inherently unlimited) of the laser gyro provide these capabilities. Laser gyros also have other outstanding features such as excellent scale factor linearity, long term stability, bias stability and insensitivity to acceleration, vibration and high-g shock. Additionally, the laser gyros have an instant-on capability, since there is no warm-up time, and are stable from turn-on to turn-on even after long periods of dormancy. They require no thermal compensation, have a very long shelf life, require less frequent periodic recalibration (about once a year) compared to their mechanical counterparts, have their own built-in test capability and are suitable for low-cost mass production. Ownership and life cycle costs are much less than the gimballed systems.

Laser gyros are inherently compact. Including electronics, three axis gyro units occupying only 250 cubic inches have been built. Complete systems require about 1000 cubic inches.

### 4.2 Aircraft Inertial Navigation

Air Force Standards for future aircraft navigation reference systems specify a position error rate of 0.8 nmi/hr for the first hour and 1.0 nmi/hr thereafter. Velocity error is specified as 2.5 ft/sec for the first two hours (Reference 11). Following is a compilation of systems designed for aircraft navigation. Only Honeywell and Sperry appear to have reached the development stage to offer production units or units designed for specific purposes.

### 4.2.1 Honeywell Systems

LINS (Laser Inertial Navigation System) - In 229 hours of flight tests conducted in 1975 the LINS system has demonstrated a CEP rate of 0.89 nmi/hr and a velocity accuracy of 3 ft/sec (References 13,14). LINS is a company development for commercial aircraft. Prototype models were to be delivered to the Boeing Company and the U.S. Government during March 1978 for further tests.

RLGN (Ring Laser Gyro Navigator) - RLGN is a variant of LINS and is being developed by the Naval Air Development Center. It is designed as a nominal 1 nmi/hr system and is being developed for multiple aircraft applications. System delivery was expected in August 1978. Flight tests will be conducted over the next two years in a Navy P-3C aircraft, an Air Force F-106 aircraft and an Army helicopter. A summary of performance specifications is given in Table 1 (Reference 15).

CAINS (Carrier Aircraft Inertial Navigation System) - This project, conducted by the Naval Air Systems Command, has produced a standardized system with at-sea alignment capabilities for five first line tactical aircraft: the F-14A, A-6E, S-3A, E-2C, and RF-4B. This system is a variant of the RLGN. Installation on an E-2C was planned for 1979 for carrier operations and evaluation of at-sea alignment and navigation capability (Reference 15).

ARINC 704 - This commercial system has been selected by Boeing for the 757/767 aircraft. Production deliveries are scheduled to begin in early 1981. Flight test results gave a position error rate (95% probability) of 1.74 nmi/hr and a velocity error (95% probability, 4 hr) of 7.22 kts.

### 4.2.2 Sperry Systems

AHRS (Attitude and Heading Reference System) - This is a generic system compatible with either the SLIC-15 or SLIC-7 laser gyro designed for aircraft environments. Analytical measurements were conducted on this system (Reference 16).

Table 1

RLGN Performance Specifications

| | |
|---|---|
| Reaction Time | <5 min |
| Position Accuracy | 1 nmi/hr CEP rate |
| Velocity Accuracy | 3 ft/sec per axis (RMS) |
| Attitude Accuracy | 2.5 arc min (RMS) |
| Heading Accuracy | 3.0 arc min (RMS) |
| Acceleration Capability | 10 g's each axis |
| Rate Capability | 400 deg/sec each axis |
| Reliability | 2500 hr MTBF |
| Test Provisions | BIT, incl. sensors |
| Environmental Capability | MIL-E-5400 and MIL-STD-810C |

Differential Omega-Ring Laser Strapdown Aircraft Navigator - This hybrid system uses a laser gyro similar to the SLIC-15 in conjunction with the Differential Omega navaid system and is designed for aircraft environments. It is an inertial mixed navigation system that produces a truly synergistic navigation capability. This results in a very accurate position and velocity measurement (Reference 17).

## 4.3 Weapon Guidance

Laser gyro strapdown systems find wide application in missile midcourse guidance and control. However, the primary concern in tactical weapon delivery system development is low acquisition cost. Tactical weapon systems which require inertial reference systems are: Wide Area Antiarmor Munition (WAAM), Advanced Conventional Standoff Missile (ACSM), GBU-15 Glide Bomb, and Advanced Medium Range Air-to-Air Missile (AMRAAM) (Reference 12).

Table 2 shows an approximate set of laser gyro requirements to satisfy the typical inertial air-to-surface missile mission. Latest technology gyros using mechanical dither or magnetic mirror biasing have achieved the requirements outlined. Higher grade performance (0.1°/hr) would require something like a differential gyro (DILAG).

Table 2

Inertial System Requirements

| | |
|---|---|
| Residual Bias Drift | |
| Horizontal Axes | 0.1°/hr |
| Vertical Axes | 1.0°/hr |
| Random White Noise Drift | $0.03°/\sqrt{hr}$ |
| Random Markovian Drift (1 hr correction time) | 0.1°/hr |
| Scale Factor Stability | 200 PPM |
| Scale Factor Asymmetry | 10 PPM |
| Rate Range | 100-400°/sec |

Some specific systems are the following.

<u>LCIGS (Low Cost Inertial Guidance System)</u> - The Air Force Armament Laboratory is developing this system concept for mid-course guidance of tactical air-to-surface missiles. It employs a modular concept which contributes to its low cost. This system is technology independent down to the sensor level.

### 4.3.1 Honeywell Systems

<u>ATIGS (Advanced Tactical Inertial Guidance System)</u> - This program is being conducted by the Naval Weapons Center, China Lake, for the development of a low cost inertial midcourse guidance system for air-to-surface missiles. The original system was delivered for flight tests in May 1974 and has undergone over 40 captive flight tests totaling 100 hours. Performance of the system steadily improved during this period from an initial CEP rate of 3.5 nmi/hr to 1.25 nmi/hr (Reference 18).

<u>SIG-D (Simplified Inertial Guidance Demonstration)</u> - An evolution of the ATIGS system, SIG-D is being developed by the Army Missile Command to demonstrate guidance and control and propulsion technologies for an extended range surface-to-surface missile. The program, which began in March 1976, includes hardware-in-the-loop simulations at MICOM, sled testing at Holloman AFB, and the firing of three test vehicles at White Sands Missile Range (Reference 18).

### 4.3.2 Sperry Systems

<u>SLIC-15 Laser Gyro IMU</u> - The Sperry SLIC-15 laser gyro IMU was integrated into a tactical missile midcourse guidance system under the Air Force Radiometric Area Correlation Guidance (RACG) flight test program. Flight testing of the SLIC-15 IMU was scheduled for the spring of 1976 onboard a C-141 and a T-33 aircraft. Results of those tests are not available; however, previous flight testing of Sperry ring laser gyro units performed by NASA at the Marshall Space Center showed performance to be 3 to 5 nmi/hr. The SLIC-15 laser gyro characteristics are shown in Table 3. (References 19,20)

Table 3

SLIC-15 Laser Gyro Characteristics ($1\sigma$)

| | |
|---|---|
| g Insensitive Drift (Turn-on Repeatability) | 1.0°/hr |
| White Noise Random Drift | $0.03°/\sqrt{hr}$ |
| Markovian Random Drift (>1 hr correlation time) | 0.1°/hr |
| g Sensitive Drift | NIL |
| Anisoelastic Drift | NIL |
| Scale-Factor Nominal Value | 3.3 arc-sec/pulse |
| Scale-Factor Stability | 0.01% |
| Scale-Factor Linearity | 0.01% |
| Sensitive-Axis Alignment Stability | 6 arc-sec |

SLIC-7 Laser Gyro IMU - SLIC-7 laser gyro units were fabricated for the Army for use as a tactical missile directional control system.

## 4.4 Ballistic Missiles

One area for which strapdown systems are particularly suitable is that of re-entry vehicle guidance. The adverse acceleration environment experienced in this application makes the characteristics of the laser gyro attractive. A program is being conducted at the Space and Missile Systems Organization to investigate such laser gyro systems. This system, developed by Honeywell, is referred to as DINS (Dormant Inertial Navigation System). Flight testing will be conducted with equipment aboard the Advanced Maneuvering Re-entry Vehicle (Reference 12).

In the area of ballistic missile defense, Sperry is developing a three-axis laser gyro using the SLIC-7 sensor for use in a strapdown system for the Army's Advanced Interceptor Missile Subsystem (AIMS) program, an adjunct of the Army's Ballistic Missile Defense System Technology Program. Extremely high input rates along with a high acceleration and shock environment dictated the use of the laser gyro for this application. Design goals are $\pm 1000$ deg/sec with overload limits of $\pm 5000$ deg/sec. (Reference 20)

## 4.5 Gun Fire Control

Sperry, under Navy sponsorship, has developed a laser gyro shipboard stable element which provides stabilization data to gun laying computers. This system, designated the MK 16 MOD 11, provides significant improvements in reliability, maintainability, accuracy, and operational flexibility. The function of the MK 16 MOD 11 stable element is to provide stabilization of the gun director and the gun order outputs of the fire control system against the effects of a ship's roll, pitch and yaw motions. Initial sea trials were very successful. Three SLG-15 laser gyros are used in this system as part of the sensor and are similar to those used in the SLIC-15 laser gyro. This system may

represent the first large production application of laser gyro systems. System parameters are shown in Table 4. (Reference 21)

Table 4

MK 16 Stable Element RLG Parameters

| | RMS Value |
|---|---|
| Bias | 1°/hr |
| White Noise | 0.03°/$\sqrt{hr}$ |
| Random Drift (1 hr correction time) | 0.1°/hr |
| Scale Factor (nominal) | 1.6 arc-sec/pulse |
| Scale Factor Stability | 0.1% |
| Align Stability | 0.1 arc-min |

### 4.6 Space Vehicles

Future space missions will require low-cost equipment that can perform satisfactorily with very high reliability. For inertial measurement functions, the laser gyro fills this requirement. Sperry, under NASA sponsorship, has developed a unique IMU configuration utilizing six laser gyros in a dodecahedron array. Reliability of the system is inherent in that three failures can be tolerated. Low-cost is affected by replacing the normal system redundancy requirement by a single system. This system uses six Sperry Model ASLG-15 laser gyros. A flight demonstration of this system was scheduled for 1976. (Reference 22)

### 4.7 Other Applications

In addition to the applications already cited, laser gyro strapdown inertial guidance systems are suitable for other applications as well. Some of these are listed below.

- Guided Glide Bombs - provides navigation information so that a terminal or midcourse fix sensor can capture the target and provide pointing and stabilization data to the terminal sensor and body motion data for flight control.

- Torpedos - provides body motion and heading data for torpedo trajectory stabilization and control.
- Aircraft Attitude and Heading Reference - in conjunction with true air speed and magnetic heading sensors provides all necessary body rate and body acceleration sensing along with attitude information. May also be used for input data to Synthetic Aperture Radar signal processing systems where vehicle motion is required.
- Spin Rate Sensor - this application for missile control makes use of the wide dynamic range capability of the laser gyro.
- Cruise Missiles - laser gyro inertial guidance systems can supply data required for guidance, autopilot, and other reference functions.
- Spacecraft Attitude Reference - provides highly accurate attitude control for applications such as the NASA space telescope and other satellites.
- Pointing and Tracking - provides stabilization information for systems requiring accurate pointing, such as large antennas, guns, telescopes, or lasers.

## 5. COMPANIES DEVELOPING LASER GYROSCOPES

In addition to Honeywell and Sperry, other companies are involved in laser gyro R & D. Among the principal U.S. companies are Litton, Northrup, Raytheon, Rockwell, Singer/Kearfott, and Hamilton Standard. Much additional work is being conducted through Government research laboratories. Both four wave and two wave systems are being investigated and developed.

Only Honeywell, at this time, appears ready for laser gyro production. Currently it is building a 4,400 square foot manufacturing facility capable of producing 30 laser gyros per month. The new facility has been designed to be expandable to make more than 300 laser gyros per month.

## 6. CONCLUSION

The foregoing sections have attempted to define the basics of ring laser gyroscopes. Historical background and development, theory, mechanization, errors, biasing, alternatives and applications have been presented. A chronological bibliography of some of the significant literature is also presented. As ring laser gyroscope technology has matured over the past decade and a half, a large amount of literature has been written on the subject, with most of it openly available.

One subject that has not yet been addressed, however, is the current state of the art of laser gyroscopes. A review of efforts of domestic developers and producers is needed to provide information on current specifications, mechanical and electrical characteristics, unit costs, test results and data, and system applications.

Lastly, the ring laser gyroscope shows great promise as a future position measuring device; however, many problems have yet to be solved before it has widespread use in tactical weapons.

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